Lunar Scout Infrared Detector (1, S11<1>): simple low-cost imaging spectrometer

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ABSTRACT

A novel design for a compact, light weight, imaging spectrometer has been proposed for an orbiting Lunar mapping mission. Simple in de sijts, dual arm optical system employs a transmission grating and a dichroic mirror 10 provide continuous two-octave spectral response. The grating's first order wave.lc.IIg[hs are reflected into the SWIR arm, while the second order wavelengths arc. transmitted to the. VNIR arm. The instrument design is that of a push broom camera. It uses one of the detector(s) dimensions for spectral selection, the other detector(s) dimension for cross-track spatial selection, and the forward motion of the platform (in this case, a spacecraft) for down-track spatial coverage.

There are two detector allays. One is a Silicon area array viewing the VNIR sc.co]]d-order spectrum in one arm of the spectrometer, and the other a HgCdTe area array viewing the SWIR spectrum in the second spectrometer arm. By judiciously choosing the total spectral bandwidth (().45 - 1.8 μm), a design using only off-the-shelf transmissive optical lens assemblies is possible. Optimizing the IR detector for an operating temperature attainable with a low-power (~ 6 Watts) thermoelectric cooler (TEC) provides satisfactory system performance. Identical array geometry in both detectors yields spectrally contiguous data that requires no re-sampling. Having few operating modes allows a control electronics implementation with simple logical elements. The complete instrument (optics, detectors, coolers, and electronics) has no moving parts and occupies a volume of less than ().()? m^3. It weighs less than 11 kg.

1.0 INTRODUCTION

1.1 Mission

The Lunar Scout Mission was intended to provide information identifying and quantifying minerals present in lunar soil such as basalts and mafic minerals, as well as determining the relative mineral composition of lunar soil. These minerals can be remotely sensed and discriminated within the 0.3-().7 μm and ().'/- 1.6 μm bands, respectively. 'The recommendations[1] for an instrument to perform these measurements from an orbit around the Moon were for a spectral response of ().3- 0.7 μm @ <10 nm resolution, ().6- 1.6 μm @ 10 nm resolution, and 1 .6-2.4 μm @ 20 nm resolution. The recommended sig[lal-lo-noise was greater than 500" @ ().1 albedo, and the recommended minimum spatial resolution was 500" lllcle.rs/pixel.

The rc.quilt.(i mission life. was to be one year with a goal of two years. There was an extreme power restriction with only about 20 watts available for the instrument. The mass and size

[1] Lunar Exploration Science Working Group, LEXWIG. Workshop held April 20, 1992, Phoenix, Az.

constraints dictated that the instrument weight be low, and we endeavored to keep it below 20 kg.

1.2 Performance Requirements

The design of a space flight instrument is usually based on its performance requirements. This often results in a design that uses state-of-the art or new technology development for components and/or processes. While this can be esthetically pleasing and provide the opportunity to advance technology, the price paid in time and dollars is frequently large. In this instrument we were presented the opportunity to design an instrument that could perform a good job of returning some subset of the desired science measurements while rigorously maintaining a specific development schedule and cost. To be sure there were less flexible design requirements including mass, power and lifetime allocations, as well as those related to orbital altitude and coverage, but the most rigidly followed constraint was that of cost. Consequently, the science recommendations were used not as the test for the appropriateness of the final design, but rather as the starting point for arriving at a design. We resolved to design this instrument at low-cost" and low-risk, and with off-the-shelf components wherever possible. The purpose of LSIRD was to return good science at low cost; not to necessarily advance the state of the art of spectrometer design.

1.3 Design Requirements

In the usual process of designing an instrument like LSIRD (pronounced Lizard. This name was whimsically proposed at an early design team meeting by one of our team members who prefers not to be identified. The name, however, stuck) a hierarchy of design requirements results from examining the performance requirements and then by postulating a combination of components, subsystems, technologies, etc., that would meet those performance requirements. After determining how each of these subsystems interrelate, and what accommodations needed to be made to assure compatibility in a "system" design, a complete set of design requirements is generated. It was recognized, early on, that an imaging spectrometer, covering continuously the broad spectral range of 0.3 to 2.4 nm and retaining a S/N > 500" over wavelength @ albedo = 0.1% could not be built for the $6 Million figure that was our target. Further, the required maximum development time of 15 months from startup to delivery to the spacecraft integrator precluded any long lead time, high risk elements, or the invention of new technology.

The LSIRD team consequently accepted the "design-to-cost" philosophy. Each element of what was perceived to be the performance requirements was instead assumed to be a performance goal. None was to be held sacrosanct. but each was examined with respect to how time and/or cost saving could result from relaxing that seal. Interaction with members of the science community specializing in lunar spectroscopy identified those areas of spectral coverage most critical to the mapping of lunar minerals.

It was obvious that the long-wavelength end of the recommended coverage was well within the performance attainable with detector technology then in existence. However, the detector would require cooling to -/0- 130K. It was also apparent that optics that operated to 2.4 μm could be either totally reflective, or if refractive built from an exotic material. Either case presented problems that were expensive and time-consuming, and could be difficult to align. The third challenge was the available method for cooling the detector. A passive radiator would require an unobstructed field of view of space that was larger than was available. from the proposed orbit of 100" km. Also, passive radiator designs in the past[2] revealed that these devices were difficult to design and build and could represent an opportunity for cost growth. Mechanical (Stirling cycle) coolers easily reached the desired temperatures but presented power and lifetime concerns. Thermoelectric coolers were reliable and cheap but could not reach the necessary temperature.

While we discussed these issues, trading the relative merits of each, a solution started to emerge. If we relaxed the long wavelength cutoff limit to 1.8 μm a number of problems were eliminated. First, the optical elements could be transmissive using glass as the refraction medium. Second, the detector(s) would not need to be as cold as they would if a 2.4 μm cutoff were required. And third, the cooling device could be thermoelectric which was simple, cheap, eliminated lifetime concerns, required moderately low power, represented no development effort and had been flown in space numerous times. We also decided that a two arm spectrometer design using a dichroic beamsplitter would become our baseline. This would allow us to use two detector arrays, one for the visible (silicon, Si) and one for IR (mercury cadmium telluride, HgCdTe). By selecting detector designs that had the same pixel pitch for visible and IR, we could eliminate any resampling requirements. Although some additional capability in the 1.8 to 2.4 μm region would be required, it would not be as a continuous spectrometer and we decided on using spot radiometers for this coverage. They will be described subsequently.

Ultimately it was a modification of the performance requirements (wavelength coverage) that yielded the best design for the available resources. This design can be seen in Figure 1.

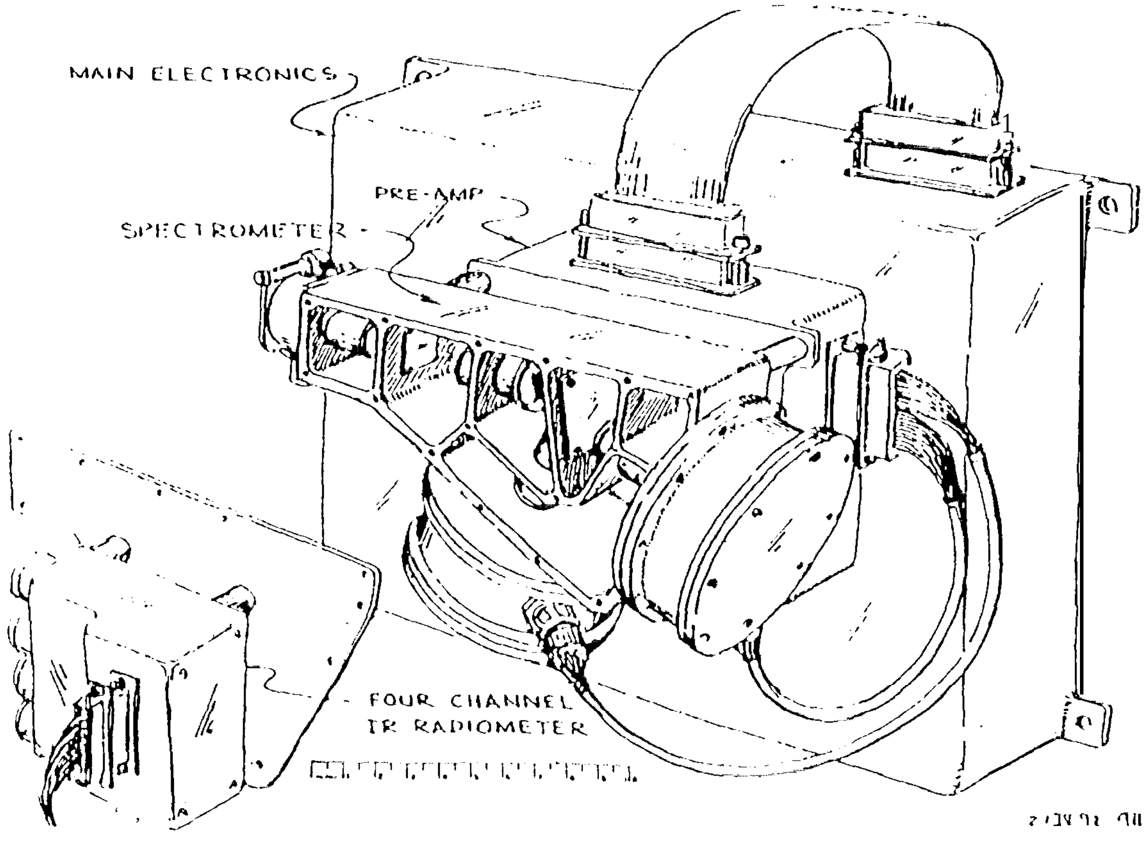

Figure 1: Lunar Scout Infrared Detector (LSIRD)

[2] E.G. Galileo/Near-Infrared Mapping Spectrometer

2.0 INSTRUMENT DESCRIPTION

2.1 Detectors

The LSIRD visible spectrometer detector chosen was a Reticon RA128x128 FET switch silicon photodiode array. This detector has been in production at Reticon for over 10 years and although not the best technology available., provides high reliability at a low cost.

An 128 x 128 array of silicon photodiodes integrate the incoming signal. Each pixel is connected to one of two Bucket Brigade Devices (BBDs) via a FET switch. A digital shift register connects each row of pixels to the BBDs in turn, the FET switches are close.d and the. charge generated in the photodiodes loads the BBDs and is readout. The pixels are connected to the BBDs in an odd even manner (i. e., pixels 1, 3, 5, etc. are connected to the odd BBD and pixels 2, 4, 6, etc. are connected to the even BBD).

"Table 1 provides a short list of the visible spectrometer detector parameters. The detector will operate at 0°C, a temperature easily obtained by a single stage thermoelectric cooler.

Table 1: LSIRD Visible Spectrometer Detector Parameters.

Parameter	Value
Array Type	Reticon RA128x128
Spectral Range	0.45 µm to 0.9 µm
Array Size	128 x 128 pixels
Pixel Pitch	60 mm x 60 mm
Active Area Fill Factor	70%
Dark Current at 0°C	80,000 electrons/sec
	45% @ 0.4 µm
Quantum Efficiency	60% @ 0.6 µm
	35% @ 0.8 µm
Readout Noise	2,500 rms electrons
Full Well	4.5 x 10^6 electrons
Integration Time	100 msec
Readout Rate	165 kpixels/sec
Operating Temperature	0° C
Cooler Type	Single Stage
	Thermoelectric Cooler

The criteria used in the selection of the detector material for the IR spectrometer was high temperature operation. The Earth is a hot body and the low orbit altitude made the large views of cold space needed for passive radiative coolers difficult to obtain. Tactical coolers (mechanical) were deemed to be too unreliable and consumed too much power for implementation on this mission. This left thermoelectric coolers, which can reliably achieve temperatures of 220K, as the coolers available for consideration. Given the cutoff wavelength of 1.8 µm, two detector materials were possible candidates for an IR detector which operates at 220 K. These material are mercury cadmium telluride (HgCdTe-1.8 µm cutoff) or indium gallium arsenide (InGa As). We chose mercury cadmium telluride because it is the. more mature. technology.

Next, we addressed the multiple.xer technology. Here we desired demonstrated, off-the-shelf technology. The multiplexer needed large capacitance to handle the large signals the moon generates, 220 K operation commensurate with TEC cooling, and high readout speed to obtain the required spatial sampling. No off-the-shelf multiplexers were able to meet these. requirements. However, Rockwell International has developed an architecture called capacitive transimpedance amplifier (CTIA) which could meet the above requirements. This technology has been demonstrated in multiplexers with different formats than the one required for LSIRD and is the approach we chose for the multiplexer for the IR detector.

Within each unit cell (or pixel) of the CTIA multiplexer is a capacitor which integrate.s the signal generated by the HgCdTe photodiode and an amplifier. This allows the HgCdTe diode to operate near zero bias for lower noise and a more linear response. The amplifier gives the signal enough gain 10 overcome the noise generated by the readout process for overall low noise performance. Each unit cell is selected for readout by two digital shift registers (i. e., one shift register selects row position and the other selects column position, which uniquely cic.fines each pixel site).

"1'able ? provides a short list of parameters for the IR spectrometer detector.

Table ?: LSIRD Infrared Spectrometer Detector Parameters

Parameter	Value
Detector Material	Mercury Cadmium Telluride (HgCdTe)
Spectral Range	0.9 µm to 1.8 µm
Array Size	128 x 128 pixels
Pixel Pitch	60 mm x 60 mm
Dark Current at 220 K	8×10^6 electrons/sec
Quantum Efficiency	50% @ 0.9 µm 70% @ 1.8 µm
Multiplexer Type	Capacitive Transimpedance Amplifier (CTIA)
Readout Noise	500 rms electrons
Full Well	2×10^6 electrons
Integration Time	100 msec
Readout Rate	165 kpixels/sec
Operating Temperature	220K
Cooler Type	3-Stage Thermoelectric Cooler

Each detector was to be mounted in an identical vacuum housing with a TEC. The Visible detector requires only a single Stage TEC, for stabilization, while the IR detector temperature necessitates three stages. By careful baffling, the IR detector can be kept at 220K with only 6 Watts input power to the TEC. These TEC's have been flown previously[3] and

[3] E.G. Hubble Space Telescope/Wide Field Planatary Camera

have demonstrated reliability, while remaining an "off the shelf" item. The ability to attain acceptable performance in an IR spectrometer, using so simple a cooling concept, is one of the key design features of this instrument.

2.2 optics

The LSIRD optical system is an on-axis slit spectrometer (Figure 2) whose spectral dispersion is accomplished by a transmission diffraction grating. Both the first and second order beams from the grating are imaged onto the detector arrays after separation by a dichroic filter/beam splitter.

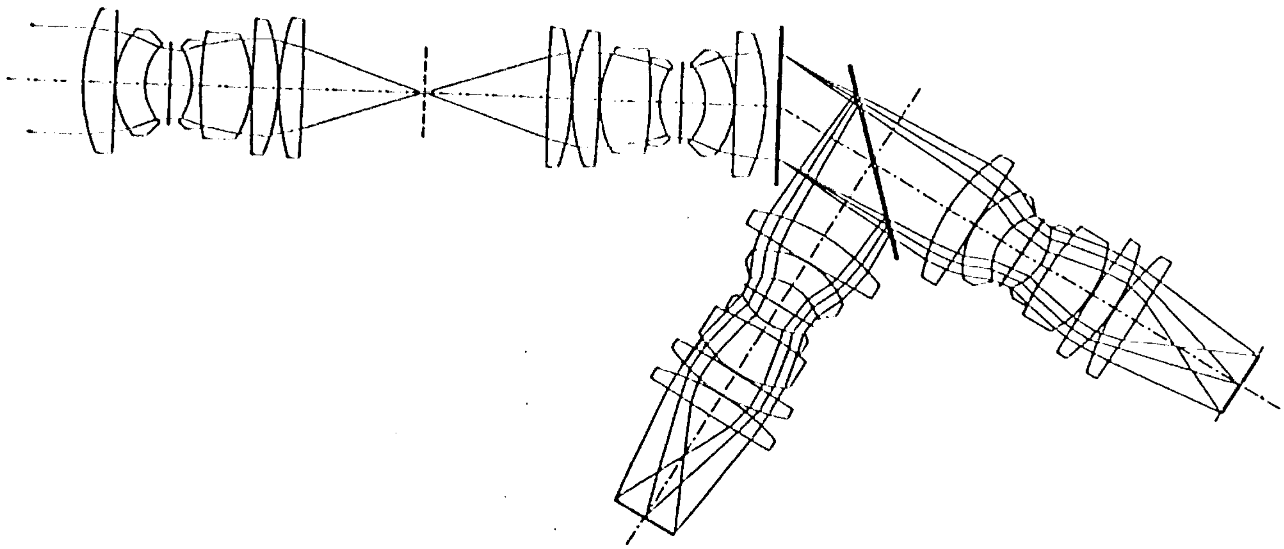

Figure ?: 1. SIRD Optical Arrangement

Four identical optics are Used: one as an objective (fore-optics), one as a collimator, and the remaining two as spectrometer cameras. This arrangement provides unity magnification and tends to prevent any aberrations inherent in the lens design from summing in an adverse manner.

Each lens is a six-element apochromat of the Xenoplan form fabricated by the Schneider Corporation. This lens type was selected for its superior color correction extending well into the infrared, and the prior space flight experience of this supplier with this design.

The lenses are re-mounted in fixed aperture and focus configuration. The necessary mounting hardware is available from Schneider, having been developed for previous space borne applications. (Vela Uniform and Spacelab Solid Surface Combustion Experiment), and qualified for both launch and on-orbit environments.

The objective lens images a cross-track strip of the lunar surface onto a slit having the same dimensions as one row of detector elements. The slit image is collimated by a second lens, reversed to the objective. The collimated beam is dispersed in the slit height direction by the transmission diffraction grating, then intercepted by a dichroic beam splitter. The first order beam is reflected into a third lens for re-imaging onto the IR detector array. The second order light is transmitted and re-imaged by a fourth lens onto the VNIR detector. A picture swath is built up as platform motion proceeds.

The effective focal lengths of the optics were selected to provide as close a match as possible between the mission (orbital) parameter set and "off-the-shelf" lens designs available. The lenses are achromatized from 0.4 µm to 1.1 µm. The first order (0.9 to 1.8 µm) image focus will be accommodated by the position of the IR detector. Lens data is listed on Table 3.

The diffraction grating (see Table 4) will provide dispersion of the 7.68 x 0.06 mm slit image. The first and second orders of the diffracted image will be separated by 90° using a dichroic beamsplitter with a wavelength cut at 0.90 µm having a 10% to 90% width of 2 nm.

To obtain radiometric data at specific wavelengths of interest outside the range of coverage of the spectrometer, four spot radiometers were added to the instrument. These comprise single InGaAs or InAs photovoltaic diodes with narrow band spectral filters and singlet silicon lenses bore-sighted with the instrument objective. The wavelengths selected (1.80, 1.85, 2.15 and 2.40 µm) provide a link to the spectrometer band edge at 1.80 µm and radiance data at wavelengths associated with expected mineral species. Ratios of radiance measurements will be used to estimate relative abundances, as well as to establish equivalent black-body temperatures.

Table 3. Lens Data

Parameter	Value
Lens Type (All)	Schneider 1.4/17
Effective Focal Length	17.56 mm
Focal Ratio (Fixed)	f/5.5
Field-of-View	24.6° x .195°

Table 4. Diffraction Grating Data

Parameter	Value
Ruling	374 grooves/mm
Incidence Angle	Normal
Blaze Angle	25.88°
Diffraction Angle - 0.9 µm	19.67°
Diffraction Angle - 1.4 µm	31.57°
Diffraction Angle - 1.6 µm	42.28°

The final optical design allowed the design of a spectrometer housing that was surprisingly small. In fact it measures only 23 x 1? x 9 cm. The entire instrument, including spectrometer, both electronic modules, and the spot radiometer measures 30 x ?7 x 30 cm and weighs just 11 kg. It rejects its waste heat to its mounting surface which needs to be at about 2"/° C, normal for spacecraft structures.

The spectrometer itself is designed to be easily **aligned** by means of sliding plates on which the slit and beamsplitter are mounted. The lenses can be focused by rotating them in their screw mounts before securing them. LSIRD is designed so that the spectrometer is insensitive to alignment degradation due to thermal expans ion.

2.3 Electronics

Each detector array requires unique and specific drive electronics. in keeping with the low-cost spirit of this design wc. decided 10 proc ure the drive elect ronic s from (be. focal - plane manufacturers. in the. case of Reticon there was work in progress to make a set of drive electronics that were flyable. For the Rockwell CTI A wc decided to use a set of demonstration board electronics and upgrade them to make them acceptable for space flight. These two boards and associated signal preamplifiers would be mounted in a dedicated package, close to the two detector housings and interconnected by removable cables and plugs.

Each spectr al region has its own A/D converter. There arc. three; one for visible, one for IR and one for the spot radiometers. In this way timing is simple and analog multiplexing is avoided. A low-power charge injection A/D converter was the choice for each. The A/D converters, array synchronization, and overall instrument timing and control was all designed from existing CMOS technology. No m icroprocessor, so ftware, memory loads, alterable, modes, variable sequences and the like could reasonably be incorporate.(i into an instrument of low-cost. low-risk design. It was further decided to procure the power supply from one of several vendors currently building such space quality devices. Although it would not be as pc.r'feet a male.il as a custo m designed power sup ply, the time and cost savings realized were. an advantageous trade.

All of the electronics, except for the previously described focal plane electronics, would be contained in a single package.. The electronics block diagram cat ı be seer ı in Fig ure 3.

2.4 Risk Management

Most elements of this design are comprised of either "off-tlic.-shelf" or mature technology items. For instance., no risk was assigned to either the electronic components or the procurement of the grating. The electronic components are all existing parts and the grating, while custom made, is readily ordered from a number of so urces.

The greatest perceived risk in the de velo p n ıcı ıt of this instrument was tile. IR detector array. Even though each element of the array had been fabricated before, and we had every reason to be lie ve this new combination of elements would yield a successful detector array at first fabrication, wc felt co mpelled to develop a strategy to recoup lost time should the detector design require refinement. We established milestones and determined that should they not be met alternative strategies would be brought into play immediately. Also, multiple examples of the arrays would be procured in various states of completion, maximizing the probability of winding up with a working dc.vice al the ship date..

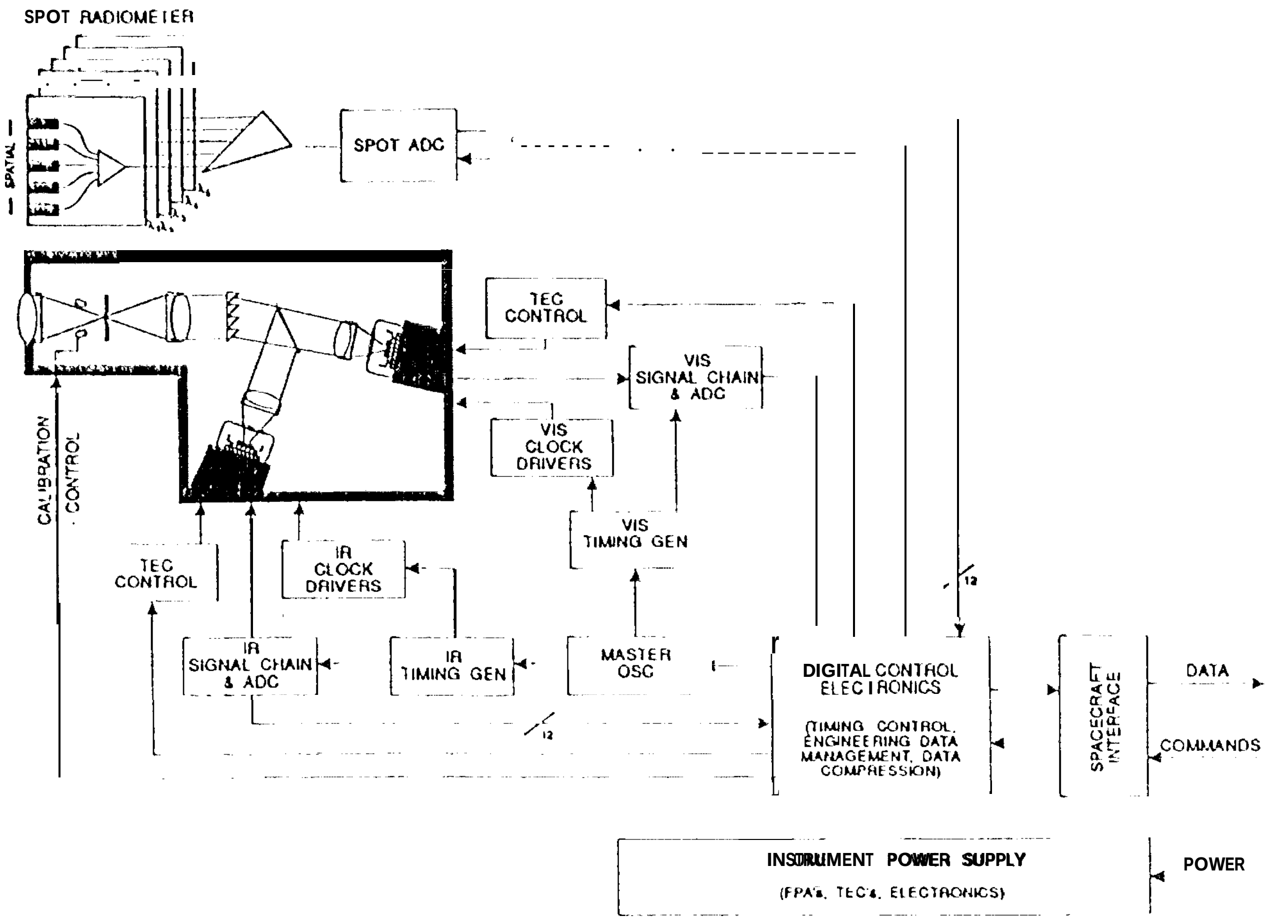

Figure 3: LSIRD Electronics Block Diagram

It was also decided to build this instrument by a cohesive, Co-located team which was composed of individuals dedicated to this task. It has been shown that this co-location can dramatically improve information exchange.

Scheduling needs to be adhered to ruthlessly and any slips require immediate replanning, with no "wail and sec" periods allowed. 'l'here needs to be in place mechanisms for anticipating delays. These include phased deliveries, building of subassembly spares, and buying rather than building components and assemblies, wherever possible. Also crucial to this type of instrument development is the. acceptance of some greater risks than would be tolerable in a long-term deep space mission. This implies acceptance testing the completed instrument rather than component level testing of each part, restricting temperature and vibration levels used in testing, and utilizing commercial parts. Here it is necessary to rely on screening, rather than pedigree to gain some measure of confidence in the parts ability to perform its roic in the completed instrument.

The basic science requirements for the LSIRD spectrometers are shown in table 5.

-1'able S: L SIRD Experiment parameters

Spectral Range	0.4 mm to 1.8 mm
Spectral Sampling	10 nm
Spatial Field-of-View	35 km
Spatial Sampling	500 m Max.
Signal-to-Noise Ratio	>500 @ 0.1 albedo

3.0 INSTRUMENT PERFORMANCE

'1'able 6 presents the system performance parameters for the L SIRD spectrometers.

l'lease remember that the lenses used 1 .SIRD are f/? but will be stopped down to any other f-ratios as require.d.

'1'able 6: LSIRD Spectrometer Performance Parameters

Parameter	Visible Spectrometer	Infrared Spectrometer
F-ratio	f/4.0	f/5.5
Etendue	1.77 x 10-6 cm2 sr	9.35 x 10-7 cm2 sr
Spectral Range	0.45 μm to 0.92 μm	0.88 μm to 1.8 μm
Spectral Sampling	~7 nm	~7 nm
Spatial Sampling	341 m x 341 m	341 m x 341 m
Integr ation Time	100 msec	100 msec
Quantum Efficiency	50% @ 0.45 μm 60% @ 0.60 μm 25% @ 0.90 μm	50% @ 0.90 μm 70% @ 1.75 μm 35% @ 1.80 μm
Johnson Noise	---	2,000 rms electrons
Readout Noise.	2 $ 500 rms electrons	500 rms electrons
Dark Current	8 x 10^4 electrons/sec @ 300" K	8 x 10^6 electrons/sec @ 220K
Thermal Background	---	974 electrons
Signal Encoding	12 bits	(0.7 μ pill 1.8 μm 1.8 μm) 12 bits

Figure 4 presents a graph of the modeled 1. SIRD performance at three albedos. The 2 channels of spectral overlap are shown. The performance in the visible is generally greater than 500" signal-lo-noise ratio, and the IR spectrometer achieves a performance generally greater than 400 sigl]al-lo-noise ratio.

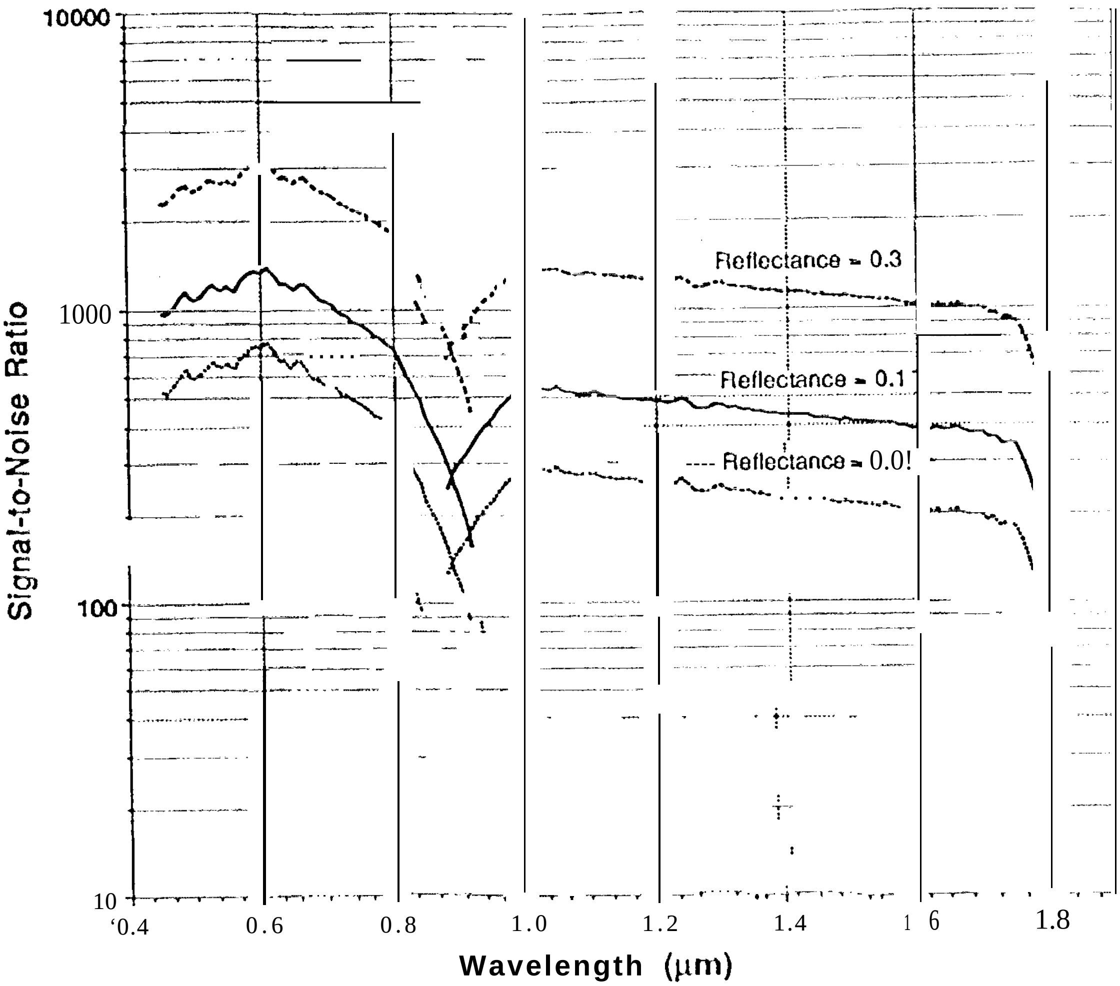

Figure 4: LSIRD Spectrometer Performance--Illumination Angle= 45°

In addition to the spectrometers, LSIRD includes a set of spot radio meters which measure the radiance at four wavelengths outside those Covered by the spectrometers. These wavelengths are critical to the identification of some of the major minerals present on the Lunar surface. The spot radiometers consist of a single f/? lens, a filter, and a single photodiode. Table 7 presents the system parameters of the spot radiometers and Table 8 gives the spot radiometer performance.

~'able. 7: Spot Radiometer System Parameters

Parameter	Value
F-ratio	f/2
Diode Type	InGaAs
Diode Size	100 mm x 100 mm
Quantum Efficiency	50%
Etendue	1.6×10^{-5} cm^2 sr
Transmission (including filter)	0.5
Filter Bandwidth	194
Sampling Time	200 msec

Table 8: Spot Radiometer Performance

Wavelength (μm)	Radiance (photons/ cm^2 sr s mm)	300 K Dark Current (electrons/ See)	Signal-to-Noise Ratio (r = 0.3)	Signal-lo-Noise Ratio 1 & &	Signal-to-Noise Ratio (r = 0.05)
1.80	4.95×10^{16}	2.5×10^{10}	3007	1016	510
1.95	4.03×10^{16}	2.5×10^{11}	855	285	143
2.15	2.86×10^{16}	2.5×10^{11}	669	223	112
2.40	2.19×10^{16}	2.5×10^{12}	181	60	30

4.0 CONCLUSIONS

By relaxing certain design requirements an instrument was designed that could return a great deal of scientific information at a low cost. By using carefully chose n of f-the-shelf Components the probability is high of delivering the instrument on time and within budge.t. The lesson for low-cost instruments ne eds to be "what **can** we do with what we have," rather than "what do we need to get what we want."

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